Compton drag as a mechanism for very high linear polarization in Gamma-Ray Bursts

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ABSTRACT
The recent claim by Coburn & Boggs to have detected a very high degree of linear polarization in the prompt emission of GRB 021206 has stimulated interest in how much polarization could arise in gamma-ray bursts from synchrotron emission. Alternatively, as Shaviv & Dar have shown, GRB polarization could be produced by inverse Compton scattering in the point-source limit. We discuss polarization from a fireball that upscatters a soft radiation field. We show that, after the proper angular integration, the residual polarization can be large, in some cases approaching the point-source limit. We discuss the probability of realizing the geometrical conditions in which a large polarization is obtained showing that, for a particularly bright burst as GRB 021206, the detection of polarization at the first attempt in the Compton drag scenario is not unlikely.

Key words: gamma-ray: bursts — radiation mechanisms: non thermal — polarization

1 INTRODUCTION

The claimed detection of a very high degree of linear polarization in the prompt emission of GRB 021206 [$\Pi = (80 \pm 20)\%$; Coburn & Boggs 2003] has triggered many theoretical interpretations. Since polarization is usually associated with some kind of asymmetry in the way the emitting material is viewed, the possible interpretations can be divided into two groups. In the first group, discussed in the observational paper itself, the asymmetry is attributed to a preferential direction of the magnetic field. Photons are supposed to be synchrotron emission from a power-law distribution of relativistic electrons; in the case of a perfectly aligned magnetic field, polarization can be as high as $\Pi_{\rm syn} = (p+1)/(p+7/3)$ where p is the power-law index of the electron distribution ($n_e(\gamma_e) \propto \gamma_e^{-p}$). A magnetic field with such an ordered configuration can not be generated at shocks (Gruzinov & Waxman 1999), and should be advected from the engine. It could be dominant in the energy budget of the outflow (Lyutikov, Pariev & Blandford 2003).

The second possible explanation invokes a particular observer set-up in order to provide the necessary anisotropy. Waxman (2003) suggested that a jet with a very small opening angle ($\theta_j \lesssim 1/\Gamma$) viewed slightly off-axis ($\theta_o \sim 1/\Gamma$ from the jet edge) would give a polarization level comparable to an ordered magnetic field even from a shock generated field (see also Gruzinov 1999 for similar considerations in the afterglow phase). The field should not be completely tangled,

but either parallel to the shock normal (Sari 1999) or contained in the shock plane (Laing 1980; Medvedev & Loeb 1999), so that relativistic aberration would cause the observer to look along the edge of the fireball and see therefore an ordered field (Gruzinov 1999; Ghisellini & Lazzati 1999).

More detailed analyses of this models (Granot 2003; Nakar, Piran & Waxman 2003) showed that the ordered magnetic field can produce a larger polarization without requiring a particular geometrical set-up. On the other hand the extreme brightness of the event ($25 - 100$ keV fluence $\mathcal{F} = 1.6 \times 10^{-4}$ erg cm^{-2}, Hurley et al. 2002) coupled with the assumption of a fairly typical redshift[1] $z = 1$ yields a narrow opening angle for the jet, making the probability of random realization of the geometrical set-up non negligible.

Synchrotron is not the only mechanism able to produce polarized radiation. In the context of a very narrow hyper-relativistic jet, in which the point-source approximation is applicable, Shaviv & Dar (1995a) discuss polarization as a characteristic signature of inverse Compton up-scatter (see also a more recent implementation in Dar & De Rujula 2003). The same mechanism was considered by Eichler & Levinson (2003), who discuss it in the framework of an

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[1] Unfortunately no optical transient has been detected for this burst, partly because the burst position was only 18° from the Sun at the moment of discovery (see Fatkhullin 2003 for a late upper limit).

ensheathed fireball. They consider the scattering of primary GRB photons, produced in the inner fast spine of the jet, by electrons advected in a slower sheath. They obtain a sizable polarization for the observed radiation under particular observing conditions.

In this paper we consider inverse Compton (hereafter IC) from a fireball with an opening angle comparable to or larger than the associated relativistic beaming (Lazzati et al. 2000; see also Begelman & Sikora 1987 for a similar scenario in AGNs). In this case the observed polarization is lower than in the point-source case due to the fact that the observed radiation comes from different angles. We numerically compute linear polarization as a function of the jet opening angle and observer line of sight. This mechanism, with respect to standard internal shocks, has the advantage of yielding a large efficiency in the conversion of bulk kinetic energy into radiation. On the other hand it does not naturally produce a broken power-law spectrum. A spectrum matching the one observed in GRBs can be obtained only under appropriate assumptions on the spectrum of the soft seed photons (Ghisellini et al. 2000).

In § 2 we describe the geometrical set-up and detail the computation of polarization from bulk Compton upscattered photons; in § 3 we compute the observed polarization from a fireball as a function of the geometrical set-up and in § 4 we discuss our results in the contest of GRB 021206.

2   COMPTON DRAG

Consider an ionized plasma moving relativistically through a photon field. A fraction $\sim \max(1, \tau_T)$ of the photons (τ_T is the Thomson optical depth) suffers inverse Compton scattering on the relativistic electrons. Their energy is increased in the scattering by a factor $\sim 4\Gamma^2$, where Γ is the electron Lorentz factor. As a net result, due to relativistic aberration, a flow of high energy photons beamed in an opening angle $\sim 1/\Gamma$ is produced at the expense of the kinetic energy of the plasma flow (see e.g. Begelman & Sikora 1987). This radiation mechanism goes under the name of Compton Drag (hereafter CD) or bulk Compton.

The possibility that the gamma-ray photons in the prompt phase of GRBs are due to the bulk Compton upscatter of UV field photons has been discussed in several geometric setup (Zdziarski, Svensson & Paczynski 1991; Shemi 1994; Shaviv & Dar 1995ab; Lazzati et al. 2000; Dar & De Rujula 2003). We here concentrate on the case discussed in Lazzati et al. (2000), in which the relativistic electrons are contained in a fireball, in contrast to the cannonball (or ballistic) approximation considered in most of the other works. Lazzati et al. (2000) showed that the mechanism can in principle give very high efficiencies, curing the intrinsic inefficiency of internal shocks (Lazzati, Ghisellini & Celotti 1999). In this scenario the shape of the soft photon field had to be selected in order to reproduce the GRB spectra. Ghisellini et al. (2000) showed that if the soft photon field has a power-law distribution of temperatures the resulting spectrum will resemble that of a GRB. Independently of the details on how the spectrum is generated, in the electron comoving frame the typical photon frequency is $h\nu \sim 1/1000/\Gamma$ keV $\ll m_e c^2$ and therefore the scattering is
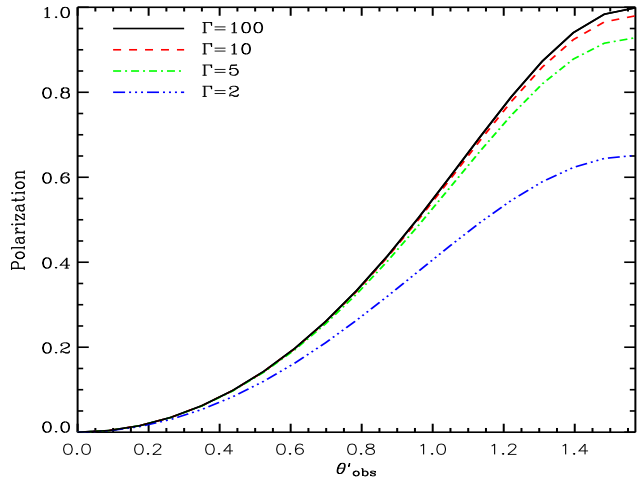

Figure 1. Linear polarization as a function of the observing angle for a single electron moving relativistically in a uniform photon field. The observing angle $\theta_{\rm obs}$, expressed in radians, is shown in the electron comoving frame. Electrons with larger Lorentz factor have more polarizing power since they see, in their comoving frame, a more anisotropic radiation field.

elastic and the polarization properties of the scattered radiation are independent of frequency. We here show that, under certain geometrical conditions, it is possible to obtain a highly polarized flux from CD.

Compton (or Thomson) scattered photons are well known to be highly polarized, with a linear polarization that depends on the photon scattering angle θ as (Rybicki & Lightman 1979):

$$\Pi = \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta} \tag{1}$$

Consider now an electron moving at relativistic speed in an isotropic photon field. In the electron comoving frame[2] photon aberration makes most of the photons arrive from one direction. The electron observes a photon field:

$$I'(\nu') = \delta^3 I(\nu'/\delta) \tag{2}$$

where $\delta \equiv [\Gamma(1 - \beta \cos \theta')]^{-1}$ is the Doppler factor. The Stokes Q parameter from a single electron can therefore be computed through:

$$Q = \int_0^{2\pi} d\phi' \int_0^{\pi} \sin \theta' \, d\theta' \, \delta^3 \, I\left(\frac{\nu'}{\delta}\right) \frac{1 - \cos^2 \theta'_{\rm sc}}{1 + \cos^2 \theta'_{\rm sc}} \cos\left(2\phi'_{\rm sc}\right) \tag{3}$$

where the polar and azimuthal scattering angles $\theta'_{\rm sc}$ and $\phi'_{\rm sc}$ are specified through:

$$\cos \theta'_{\rm sc} = \cos \theta' \cos \theta'_{\rm obs} - \sin \theta' \sin \theta'_{\rm obs} \cos \phi'$$
$$\sin \phi'_{\rm sc} = \frac{\sin \theta' \sin \phi'}{\sin \theta'_{\rm sc}} \tag{4}$$

and $\theta'_{\rm obs}$ is the observing angle with respect to the electron velocity in the electron comoving frame. Analogously, the Stokes U parameter can be obtained from Eq 3 by substituting $\cos\left(2\phi'_{\rm sc}\right)$ with $\sin\left(2\phi'_{\rm sc}\right)$. For symmetry reasons, one always has $U = 0$, so that the polarization vector is orthogonal to the plane containing the electron velocity and the
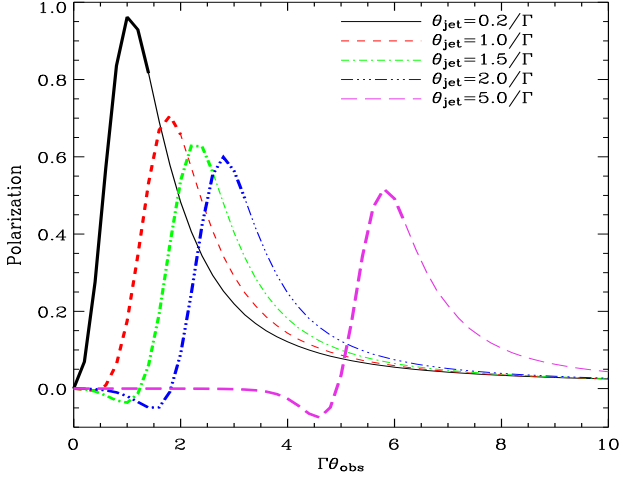
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[2] Comoving quantities are primed.

Figure 2. Polarization as a function of the observing angle θ_o in units of $1/\Gamma$ for a uniform jet with sharp edges. Different line styles show the polarization for jets with different opening angles. The lines are thicker in the region where the efficiency is larger than 2.5%.

line of sight. The linear polarization is therefore given by $\Pi = |Q|/I$, where

$$I = 2\pi \int_0^\pi \sin\theta' \, d\theta' \, \delta^3 \, I\left(\frac{\nu'}{\delta}\right) \qquad (5)$$

Eq. 3 can be numerically integrated. The resulting polarization, as a function of the observing angle $\theta'_{\rm obs}$ is shown in Fig. 1 for several values of the electron Lorentz factor Γ. In the figure a photon field $F(\nu) \propto \nu^0$ has been assumed, in order to obtain a frequency-independent result. The curves in Fig. 1 are a good approximation for any photon field that does not vary sizably over a factor of ~ 2 in frequency. The figure shows that the maximum polarization is obtained for an observer that is at $90°$ with respect to the electron velocity vector in the electron comoving frame. Also, electrons with larger Lorentz factors are more efficient polarizers, since they see a more anisotropic radiation field due to relativistic aberration. For $\Gamma \gtrsim 10$ the curves are indistinguishable and can be approximated with Eq. 1 with an accuracy of 2% for $\Gamma = 10$ and 0.1% for $\Gamma \geq 100$.

3 POLARIZATION FROM A FIREBALL

In the previous section we considered the polarization arising from the interaction of a single electron with an isotropic photon field. We here consider a jet fireball of opening angle θ_j, radially expanding at relativistic speed, observed from a viewing angle θ_o.

In order to compute the polarization that is observed from a fireball, one has to integrate the single electron polarization over the fireball surface, taking into account the angle transformations from the comoving frame to the observed one. Since a comoving observer at $90°$ transforms in an observer that makes an angle $1/\Gamma$ in the laboratory frame, one expects a maximum in the observed polarization for an observer located at $1/\Gamma$ from the edge of the jet.

The stokes vector Q (U vanishes due to symmetry considerations as for the single electron case) is given by:
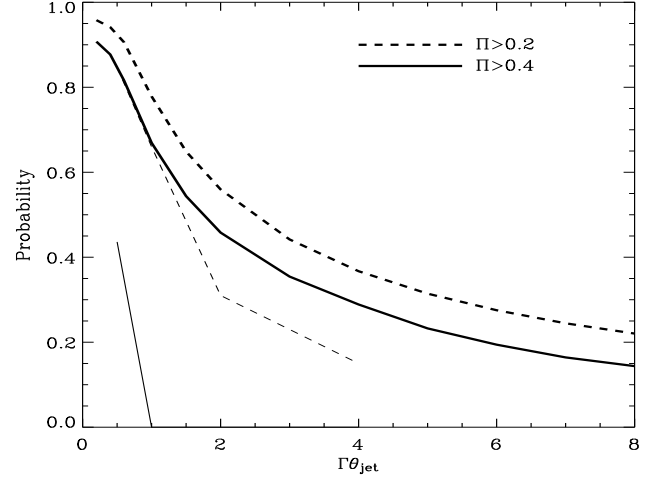

Figure 3. Probability for a random observer to detect both a bright GRB and a large linear polarization as a function of the jet opening angle in units of $1/\Gamma$ (thick lines). With thin lines we show the corresponding probabilities for synchrotron radiation from a magnetic field predominantly in the shock plane, according to Nakar et al. (2003). The actual shape of the figure is somewhat dependent on the threshold levels adopted. Also Compton drag is unable to provide a large probability for $\Pi > 60\%$.

$$Q = \int_0^{2\pi} d\phi \int_0^{\theta_j} \sin\theta \, d\theta \, \delta^3 \, I'\left(\frac{\nu}{\delta}\right) \, \Pi(\theta'_{\rm sc}) \, \cos(2\phi_{\rm sc}) \qquad (6)$$

where the Doppler factor δ must be computed as a function of the angle between the local velocity and the line of sight. The scattering angles $\theta_{\rm sc}$ and $\phi_{\rm sc}$ are as well defined in the spherical coordinate system where the line of sight is the polar axis and $\theta_{\rm sc}$ is related to the comoving scattering angle $\theta'_{\rm sc}$ through:

$$\cos\theta'_{\rm sc} = \frac{\cos\theta_{\rm sc} - \beta}{1 - \beta\cos\theta_{\rm sc}} \qquad (7)$$

Finally, $\Pi(\theta'_{\rm sc})$ is the single electron polarization computed in Eq. 3 (or, for $\Gamma \gtrsim 100$, the simpler Eq. 1).

As for synchrotron models, the observed polarization depends on two parameters (Granot 2003; Nakar et al. 2003): the opening angle of the jet θ_j with respect to its Lorentz factor Γ and the observer off-axis angle θ_o. The resulting polarization, as a function of the observer angle, is shown for several jet geometries in Fig. 2, where again the spectral dependence of the radiation has been neglected for generality. Negative polarization values correspond to polarization in the plane that contains the jet axis and the line of sight, while positive polarization values correspond to an orthogonal polarization angle. The figure shows that it is indeed possible to obtain a large degree of polarization from CD in a fireball, especially if the fireball opening angle is close to the limit $\theta_j \sim 1/\Gamma$ (the jet with $\theta_j = 0.2/\Gamma$ is shown for completeness). As in the case of synchrotron (Granot 2003; Nakar et al. 2003) the observed polarization is smaller than the maximum that can be obtained in the non-relativistic case. However, the net observed polarization from CD is larger, since the maximum comoving value is 100% rather than $\sim 75\%$ for synchrotron.

There are, however, two complications. First, the maximum of polarization is obtained for observers outside of the
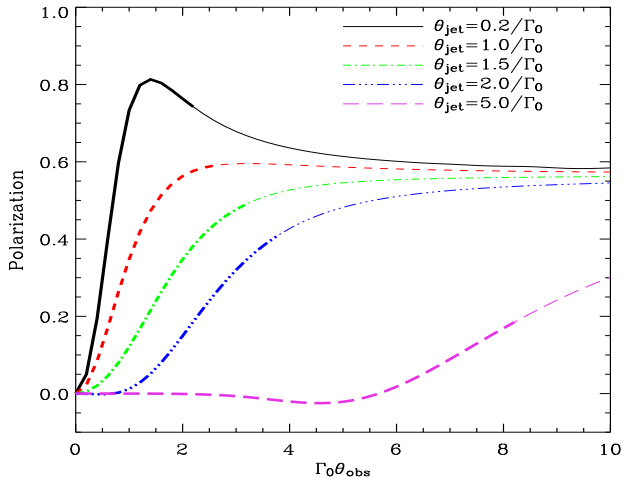
Figure 4. Same as Fig. 2 but for a Gaussian jet (see text). Since in this jet the Lorentz factor is not uniform, the observing angle θ_o is shown, in the x axis, in units of $1/\Gamma_0$, the Lorentz factor along the jet axis.
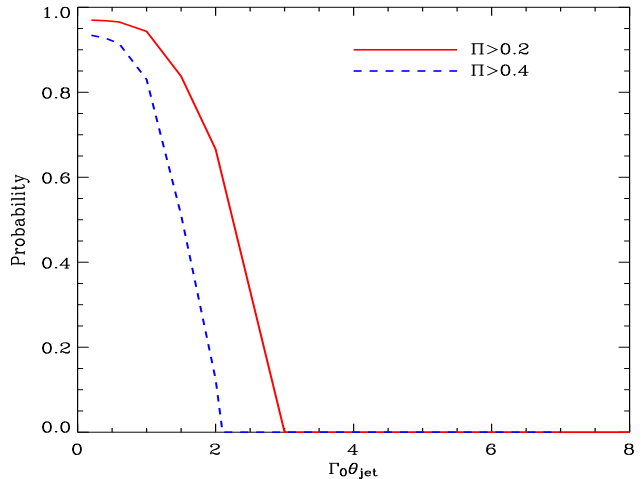

Figure 5. Same as Fig. 3 but for a Gaussian jet. In this case, the probability of observing a large linear polarization is enhanced in small jets, but quickly drops to zero for $\Gamma_0\theta_j \gtrsim 3$.

jet ($\sim 1/\Gamma$ from the jet edge). In this configuration the flux detected by the observer is smaller than the flux that an on-axis observer would detect. A highly polarized GRB should therefore appear dimmer than a non-polarized one, given the same explosion parameters. We define the efficiency ϵ as the ratio between the detected flux and the flux an on-axis observer would detect. Since GRB 021206 was a rather bright event (Hurley et al. 2002) a situation in which $\epsilon \ll 0.1$ is unlikely. For this reason we have underlined in Fig. 2 with a thicker line-style the range of off-axis directions in which $\epsilon > 0.025$. Even though the thick lines encompass the peak of polarization, it is clear that, particularly for the broader jets, only a small fraction of the random observers would detect a large linear polarization. In Fig. 3, with thick lines, we show the probability that a random observer would detect more than a threshold polarization as a function of the jet opening angle. Threshold polarizations of 20% and 40% have been assumed. For a narrow GRB jet this probability is not negligible. With a thin line we show, for comparison, the corresponding probability for synchrotron, according to the computations of Nakar et al. (2003), for an electron index $p = 3$, corresponding to $\Pi_{\rm syn} = 75\%$. It is clear that CD can produce $\sim 30\%$ larger linear polarization than synchrotron.

An interesting issue arises if the radiation efficiency of the prompt GRB phase is large enough to produce a sizable deceleration of the fireball. This may happen in CD scenarios and even at a larger extent in the synchrotron case, where only $\sim 1/3$ of the dissipated energy is radiated as MeV photons. The consequences of a deceleration of the fireball are two: both the jet geometry $\theta_j\Gamma$ and the observer geometry $\theta_{\rm obs}\Gamma$ are affected. In terms of Fig. 2 the location moves to the left on the X-axis, simultaneously jumping from one curve to another with smaller $\theta_j\Gamma$. Whether the causes an increase or a decrease of polarization depends on the starting point, what is certain is that, if the deceleration is more than a factor of $\sim 3 \div 4$ in Γ very small polarization is left.

3.1 Non uniform jets

The result we have shown are relative to sharp edged jets, i.e. jets in which the Lorentz factor and the energy per unit solid angle are constant inside the cone, dropping to zero (1 for the Lorentz factor) outside it. A more physical situation should be that of a jet with a transition region, where the energy per unit solid angle and the Lorentz factor drop smoothly from their central values to smaller ones.

In Figg. 4 and 5 we show the analogues of Figg. 2 and 3 in the extreme case of a Gaussian jet. In this jet, both the Lorentz factor Γ and the energy per unit solid angle $\mathcal{E} \equiv dE/d\Omega$ are distributed according to:

$$\Gamma(\theta) = \Gamma_0\, e^{-\frac{\theta^2}{\theta_j^2}\log 2}$$
$$\mathcal{E} = \mathcal{E}_0\, e^{-\frac{\theta^2}{\theta_j^2}\log 2} \qquad (8)$$

so that θ_j coincides with the half width at half maximum of the Gaussian. The jet has been truncated at $3\sigma = 2.56\theta_j$, and Γ_0 has been chosen large enough to ensure that $\Gamma(\theta) \gg 1$. There are two main differences with respect to the homogeneous jet. First, the polarization outside the core of the jet remains large out to wide angles, even though the total intensity drops. This effect is due to the fact that the Lorentz factor in the edge of the jet is much smaller than that in the core – which is used to define the unit on the X-axis of the figure – and therefore the observed burst properties vary more slowly with the off-axis angle. The main difference can be noticed by comparing Fig. 5 with Fig. 3. A narrow Gaussian jet produces more easily a large linear polarization, but the probability of observing such a high polarization by a random observer drops to zero much more quickly with respect to the uniform jet case.

Alternative configurations can be considered. For example, Nakar et al. (2003) consider a uniform jet with exponential wings only in the energy per unit solid angle $\mathcal{E}$ and constant Lorentz factor. What we have shown are the two extreme cases: a pure uniform jet and a jet with smooth variations of both Lorentz factor and energy, in order to encompass all possibilities.

4 DISCUSSION

We showed in the previous sections that CD from a moderately narrow jet (compared to its Lorentz factor Γ) can produce a large observable degree of linear polarization. Even though the observed polarization is larger than that attainable by synchrotron from a shock generated magnetic field (Granot 2003; Nakar et al. 2003), the condition $\Gamma\theta_j \lesssim 5$ must be satisfied in order to have a non vanishing probability of observing linear polarization at first attempt. Unfortunately it is not possible to measure either the Lorentz factor of the fireball or its opening angle, since we do not have afterglow observations for GRB 021206. Nevertheless an estimate of θ_j can be made thanks to two correlations recently discovered in the sample of well-observed GRBs. First, we use the standard beaming corrected energy for GRBs $E \simeq 5 \times 10^{50}$ erg (Frail et al. 2001). Second, we adopt the "Amati correlation", which relates the isotropic equivalent energy output of the GRB in γ-rays with the peak frequency (in $\nu F(\nu)$ representation) of its spectrum (Amati et al. 2002). For the case of GRB 021206 the observed peak frequency is $h\nu_{\rm peak} \sim 1$ MeV (Hajdas et al. 2003). Combining this information with the fluence of the GRB ($25 - 100$ keV fluence $\mathcal{F} = 1.6 \times 10^{-4}$ erg cm^{-2}, Hurley et al. 2002) we obtain $z \sim 1.5$ and $\theta_j \sim 2°$, making the jet of GRB 021206 one of the narrowest detected[3], yet comparable to the jets of GRB 990123, GRB 990510 and GRB 000926 (Frail et al. 2001). The Lorentz factor of the fireball can be estimated from the observed peak frequency. If the soft photon field is produced by a simultaneously exploding supernova (Lazzati et al. 2000), the observed peak frequency is given by:

$$h\nu_{\rm peak} \simeq 10\,\Gamma^2\,k\,T_{\rm ph} \qquad (9)$$

where $T_{\rm ph} \sim 10^5$ K is the black body temperature of the photon field. Inverting the equation we obtain $\Gamma \sim 130$. This yields, as a most probable configuration for GRB 021206:

$$\Gamma\theta_j \sim 5 \qquad (10)$$

We conclude that, if the jet configuration of GRB 021206 were sufficiently sharp-edged, polarization from CD would be a viable explanation for the RHESSI observation, even though the actual jet-observer configuration would be somewhat lucky. Under similar conditions, synchrotron radiation from a shock generated field, would produce somewhat smaller polarization.

Even though synchrotron radiation from an ordered toroidal magnetic field component advected from the inner engine is an alternative good explanation for the detected high level of polarization, we have shown that the detected polarization does not necessarily imply synchrotron as the emission mechanism (see also Eichler et al. 2003). CD has also the advantage of naturally providing a large efficiency, while it requires some ad-hoc assumptions in order to reproduce the observed spectrum. There are several ways to discriminate between the two mechanisms with future observations. First, CD requires a particular geometrical setup to produce a large polarization. As a consequence, only

a small fraction of GRBs should be highly polarized, the more luminous being more likely to be polarized than the dim ones, since they have narrower jets. On the other hand, if polarization is due to a toroidal magnetic field advected from the central source, it should be a general feature of all GRBs, irrespective of their observing angles and apparent luminosities[4]. Secondly, CD polarization is a property of the prompt event only, and the optical flash should be less polarized, while it should be highly polarized in the synchrotron case. Finally, synchrotron polarization has a well defined relation to the spectral slope of the radiation (Granot 2003; Lazzati et al. 2003 in preparation), while CD polarization should be almost independent on the spectral properties of the observed radiation.

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[3] It should be noted that in deriving the numerical values we have neglected the small efficiency implied by the measured polarization. Should it be taken into account, an even smaller opening angle would be derived (e.g. Nakar et al. 2003).

[4] Only the small fraction of GRBs observed at $\theta_o < 1/\Gamma$ from the jet axis should be unpolarized.